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TEST RESULTS FROM A BREADBOARD CRYOGENIC PROPELLANT CONDITIONING ASSEMBLY

by Henry P. Stinson, Jr.

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16. ABSTRACT

Cryogenic auxiliary propulsion systems consist of five major subsystems: propellant tanks, propellant conditioning assemblies, accumulators, propellant distribution systems, and thrustors. The propellant conditioning assembly (PCA) converts low pressure liquid to high pressure gas for use by the thrustors, and is one of the most complex subsystems of the cryogenic propulsion system. The ability to achieve rapid starts and at the same time maintain system control are two critical areas of PCA operation. To investigate these critical areas of operation, a PCA of the general type required was designed, fabricated, and tested using existing hardware. Realistic start times were achieved and system control was maintained at all operating conditions.

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INTRODUCTION

Future space vehicles which must be capable of performing a large number of maneuvers will require high performance auxiliary propulsion systems (APS). These performance requirements will necessitate using hydrogen and oxygen propellants.

APS on-off operation, fast response requirements, and combustion stability dictate that oxygen and hydrogen for the thrustors be supplied as gas at high pressure. To minimize APS weight, the propellant must be stored as liquid at low pressure, and be converted to high pressure gas for use by the thrustors. These requirements can be met by a cryogenic APS consisting of five major subsystems: (1) propellant tanks with zero-gravity acquisition devices, (2) propellant conditioning assemblies, (3) accumulators, (4) propellant distribution systems, and (5) thrustors. These elements are shown schematically in Figure 1.

The propellant tank and zero-gravity acquisition device provide low pressure liquid to the propellant conditioning assembly (PCA). The PCA is an integrated system consisting of turbopumps, heat exchangers, and gas generators (GG) which convert low pressure liquid to high pressure gas. The accumulator provides a ready supply of conditioned propellant that is delivered to thrustors through the propellant distribution system.

The PCA is a very complex subsystem of the APS. This is illustrated by considering the APS propellant conditioning assembly requirements. As thrustors fire, the pressure in the accumulator decays, and at a minimum pressure PCA operation begins. As thrustor demand flow decreases below that supplied by the PCA, the accumulator pressure will increase to a maximum level and PCA operation will terminate. Therefore, the PCA will have many on-off cycles, the number being a function of the required thrustor operation and accumulator size. This on-off operation, coupled with the interdependent components of the PCA, make the PCA a complex system.

The ability to provide system control and rapid PCA response times are two critical areas of PCA operation. Response time is defined as the time required to begin flow delivery to the accumulator after reaching the trip-on pressure (see Fig. 2). Assume that the lowest pressure in Figure 2 is the minimum pressure required for satisfactory thrustor operation. If response time is increased and accumulator size held constant, the pressure will drop below the minimum pressure required for satisfactory thrustor operation. Studies have shown that accumulator size is highly dependent on PCA response. To obtain a lightweight APS, response time must be minimized.

This report describes the design, fabrication and testing of a PCA representative of the type envisioned for a cryogenic APS. Existing hardware was used for the project. The program objectives were to demonstrate the ability to achieve realistic response times, and to provide system control.

APPROACH

To minimize system complexity and reduce program cost, a PCA was designed and fabricated for the hydrogen side only. Control and response time problems associated with this system would also be common to the oxidizer side. The resulting design is shown schematically in Figure 3.

The RL-10 turbopump was found to most closely meet the desired head and flow requirements. This turbopump was combined with two H-1 engine heat exchangers, a facility gas generator and two 0.757-m^3 high pressure facility tanks to form the major elements of the PCA. The PCA was designed to best utilize the characteristics of these components. For maximum system efficiency, the gas generator should provide the turbine working fluid; however, since the RL-10 turbine uses warm hydrogen gas ($<$ 420 K), the gas generator could not be used to provide the drive gases. This dictated that the gas generator be used only to provide energy to the heat exchanger to convert the pumped hydrogen to gas. This hydrogen gas (GH_2) was then used to drive the turbine and pressurize the accumulators. With these constraints, the best design approach was to tap off a small amount of the GH_2 downstream of the heat exchanger, use it to drive the turbine and then supply it to the gas generator to be burned. The turbine flow was regulated to a constant value by controlling a valve upstream of the turbine. Regulating this flow assured a constant gas generator mixture ratio for all accumulator demand flows.

The system was designed so that PCA operation would be initiated and terminated automatically at accumulator pressures of 276 and 552 N/cm^2 respectively. Three valves located downstream of the accumulator were used to simulate various system demand flows and initiate and terminate PCA operation.

TEST FACILITY

This program was conducted at the Marshall Space Flight Center (MSFC) component test laboratory. The major components consisted of an 18.925-m^3 liquid hydrogen tank, an RL-10 turbopump, two H-1 engine heat exchangers, a facility gas generator, and two 0.757-m^3 accumulators. The major components are shown in the photographs of Figures 4 through 7. A photograph of the entire system is presented in Figure 8. Note from Figure 7 that the liquid hydrogen tank is located on the opposite side of the stand from the pump inlet, resulting in a suction line 36.3 m long.

Temperature and pressure measurements were taken throughout the system from the liquid hydrogen tank to the accumulator and gas generator exhausts. Flow measuring devices were located in the main suction line, pump discharge line, heat exchanger outlet line, accumulator inlet line, and the inlets to the gas generator. Data from the measurements taken were recorded on magnetic tape through the digital data acquisition system, and were processed using a data reduction program written especially for this test program. Fast response measurements were recorded on a Brush recorder and oscillographs.

TEST APPROACH

Each major PCA component was tested as a subsystem prior to initiation of complete system testing. The gas generator was the first component tested. Gaseous hydrogen and oxygen were provided from a facility supply, and tests were conducted to develop a start sequence and evaluate performance over the anticipated operating range. Following the gas generator tests, the heat exchangers were installed and the gas generator/heat exchangers tested as a subsystem. This was accomplished using a facility pressurization system to pressurize the liquid hydrogen tank to achieve the desired heat exchanger cold side inlet temperatures and pressures. These tests evaluated heat exchanger performance over the expected operating range. The turbopump was the last component tested. This testing was accomplished using the accumulators as a high pressure gas source to drive the turbine. The pumped hydrogen was dumped through the gas generator and burned at the facility burn stack. These were short, 3-second duration tests, and were used to evaluate pump performance and system sequencing.

As data was generated from each of these component tests, it was used to update an analog model of the entire system. The analog was then used to help develop the system start sequence, define system operating points, and resolve problems. A description of the analog simulation and the results obtained using the model are presented in Reference 1.

GAS GENERATOR TESTING

The gas generator was a facility item originally designed to burn gaseous hydrogen and air, and required a redesign of the injector to burn gaseous hydrogen and oxygen. A new injector was designed and fabricated by MSFC. Ignition was accomplished by use of an augmented electrical spark ignitor system.

Following modification of the injector, the gas generator was tested as a component. Gaseous hydrogen and oxygen were provided from a facility supply, burned in the gas generator and exhausted through a facility burn stack. A section of ducting containing temperature rakes at several axial locations was installed where the heat exchangers were to be located. These measurements were to assure that a satisfactory temperature profile was obtained with the new injector.

A problem was encountered during the initial phase of testing. Ignition did not occur during the first test. The mixture ratio (O/F) during transition was not high enough to assure ignition. A valve sequence was developed which provided a high mixture ratio for a short duration early in the transient and lowered the mixture ratio to the desired steady state value after ignition. Following development of a satisfactory start sequence, tests were conducted over a range of propellant inlet conditions and mixture ratios. No problems were encountered, and satisfactory temperature profiles were obtained over the anticipated operating range.

GAS GENERATOR/HEAT EXCHANGER

The H-1 engine heat exchangers were originally designed to use liquid oxygen in the cold side and oxygen/kerosene combustion products in the hot side. For use in the PCA, the heat exchangers were required to operate with liquid hydrogen in the cold side and oxygen/hydrogen combustion products in the hot side. It was the purpose of this phase of testing to evaluate heat exchanger performance using the fluids required for PCA operation, and to investigate system sequencing.

The facility configuration for the performance evaluation is presented in Figure 9. Operating points were obtained for various hot side mixture ratios, inlet temperatures, and hot and cold side flows. For comparison purposes, the data was corrected to a standard set of inlet conditions. This was accomplished using a linear interpolation of data from the analytical model. The corrected test data is compared to the analog model predictions in Figure 10. Two curves are presented, one representing the original model and one the updated model. The original model was based entirely on analysis, whereas the updated model was adjusted to fit the test data. The model was adjusted by setting the hot side parameters equal to the test values and by adjusting the heat transfer coefficients until the cold side parameters matched the test data. As seen from Figure 10, the original model predicted a cold side temperature rise approximately 18 percent lower than the test data.

Following the steady state evaluation, tests were conducted to demonstrate the performance of the turbine flow controller and to investigate system sequencing. Flow control was achieved by maintaining a constant pressure to square root of temperature ratio ($P/\sqrt{T}$) at the turbine inlet. Flow through the turbine nozzles was choked; therefore, maintaining $P/\sqrt{T}$ constant at the turbine inlet assured constant flow through the turbine. This method of flow control was implemented by using an electrohydraulic valve at the turbine inlet, and by locating pressure and temperature measuring devices between the valve and turbine inlet. The pressure and temperature measurements were routed to a controller where the $P/\sqrt{T}$ ratio was calculated, compared to a reference value, and an error signal generated. The turbine inlet valve was then modulated to null the error signal.

To evaluate the effectiveness of the flow controller, tests were conducted with and without the flow controller in operation. Figure 11 is a schematic of the facility with the controller installed. During those tests with an inactive controller, the pressure upstream of the gas generator fuel valve was regulated to a constant value. With the controller installed, a constant value of the $P/\sqrt{T}$ ratio was maintained at the inlet to the gas generator fuel valve. Essentially identical tests were conducted with the two methods of control. The results are compared in Figures 12 through 14. The controller maintained a constant gas generator fuel flow, resulting in a constant mixture ratio and a more stable combustion temperature. Using the flow controller, gas generator and turbine operation are practically independent of the remainder of the system.

This phase of testing verified heat exchanger performance, and demonstrated the ability of the turbine flow controller to maintain constant flow.

TURBOPUMP TESTING

Turbopump component tests to evaluate pump performance and investigate system sequencing were conducted prior to system tests. This was accomplished using the accumulator as a high pressure gas source to drive the turbine. The valve sequence developed for the complete system was used, with the exception that the gas generator oxidizer valve remained closed. Hydrogen gas flowed from the accumulator through the turbine and gas generator to the facility burn stack. Using this approach, a pump test duration of 3 seconds was planned.

One major problem was discovered during turbopump testing. This problem related to the suction line configuration (Fig. 15). The long line coupled with the PCA fast start requirements resulted in severe inlet pressure oscillations. Pump inlet pressure is plotted versus time in Figure 16 for the first pump test. A very large pressure drop occurred when flow accelerated during the start transient, and was followed by a high amplitude pressure surge. These pressure oscillations were sustained for the test duration. It was theorized that the high line inertance (436 sec^2/m^2) coupled with the fast start transient resulted in a momentum pressure drop which caused the pump to cavitate. When cavitation head loss in the pump occurred, the high pressure downstream of the pump caused flow within the pump to reverse, resulting in the inlet pressure surge. The alternate surging and cavitating was self sustaining. This theory is supported by the data presented in Figures 17 through 20. The decrease in pump discharge pressure and corresponding increase in pump speed are indicative of cavitation head loss. The sharp increases in pump inlet and discharge temperatures and the sharp spikes in pump inlet pressure indicate a flow reversal within the pump.

A high amplitude inlet pressure surge problem was also noted at cutoff (see Fig. 16). This surge was accompanied by a rapid decrease in pump speed to zero followed by reverse rotation to 14 000 rpm and an increase in pump inlet temperature (Figs. 18 and 19). Data indicated that this surge was caused by expansion of the hydrogen trapped between the pump discharge and the check valve which isolated the pump and heat exchanger. The valve was located 6.1 m downstream of the pump, resulting in a volume of 0.013 m^3 of supercritical hydrogen which would expand back through the pump at cutoff.

Several actions were taken to solve these problems. The pump start transient was slowed by extending the opening time of the turbine inlet valve. The valve opening time was changed from a fixed value of 0.2 seconds to a controlled ramp of 50 percent open per second. It was estimated that this would result in a transient of approximately 0.5 seconds. Using this start transient, an analysis of the feed system indicated that the momentum pressure drop would be reduced sufficiently to avoid the alternate cavitation and surging of the pump. Additional net positive suction head (NPSH) margin was provided by increasing the prestart inlet pressure from 40.7 to 44.9 N/cm^2, and by providing colder propellant at the inlet to the pump.

To reduce the magnitude of the pressure surge and reverse rotation at cutoff, the check valve isolating the pump and heat exchanger was relocated to within a few centimeters of the pump discharge. This minimized the volume of trapped hydrogen that could expand back through the pump.

With the above changes incorporated, the pump inlet pressure surge and increase in pump speed at cutoff was reduced to an acceptable level. However, the inlet pressure oscillations were not eliminated. Pump inlet pressure is plotted versus time in Figure 21. A comparison of the Figure 21 data with those of the previous test (Fig. 16) shows that the initial pressure drop due to flow acceleration was decreased significantly; however, the system still oscillated.

The primary cause of the oscillations still appeared to be cavitation at the pressure minimum, resulting in loss of pump developed head and subsequent flow reversal within the pump. Pump inlet temperature, discharge temperature, discharge pressure, and pump speed (Figs. 22 through 25) support the alternate cavitating/surging theory. The decreases in pump discharge pressure and corresponding increase in pump speed indicate cavitation head loss. The pump inlet and discharge temperature spikes indicate flow reversal within the pump.

Pump inlet pressure and temperature at each pressure minimum are presented in Figure 26. With the exception of one point, the inlet conditions at the minimum pressures are within allowable RL-10 operating limits. Based on these data, the conclusion can be made that the pump did not cavitate at the minimum pressures.

Although the inlet pressure and temperature data of Figure 26 indicate that sufficient NPSH was available, the majority of the data support the hypothesis that cavitation caused the observed oscillations. Two possible explanations for the discrepancy are that

(1) the pump inlet pressure and temperature measurements were in error, and (2) the pump was operating at a high flow condition where the normal NPSH requirements were not applicable. No reason could be found to suspect the reliability of the pump inlet pressure and temperature measurements. Therefore, the most probable explanation was that cavitation resulted from operation at high flow.

A high flow was possible because the pump discharge bleed valve (see Fig. 3) had remained open for the test duration. Normally this valve would close when sufficient discharge pressure was developed to overcome the check valve isolating the pump and heat exchanger. The pump discharge bleed valve was open during the start transient to prevent pump stall caused by dead-heading the pump. To reduce pump flow in order to prevent recurrence of the oscillation problem, the bleed valve was sequenced to close 0.7 seconds into the run. Analysis showed that this should allow sufficient time to avoid stalling the pump and at the same time should prevent a high flow. With this change, the inlet pressure oscillations were eliminated (see Fig. 27), and satisfactory pump operation was demonstrated.

PCA SYSTEM TESTS

The first PCA system test was terminated prematurely by the gas generator overtemperature. With a full demand on the accumulator, the gas generator fuel flow required approximately 2.5 seconds to reach the nominal flow of 0.51 kg/sec. The pressure upstream of the gas generator oxidizer valve is regulated to a constant value and is independent of system operation. Therefore, when the gas generator oxidizer valve is opened the oxidizer flow reaches its steady state value faster than the gas generator fuel flow. During the first test, this fast response of the oxidizer flow, coupled with the slow response of the fuel flow, resulted in an overtemperature cutoff. The solution to this problem was to operate the gas generator oxidizer valve in two steps. This resulted in an oxidizer flow transient which matched that of the fuel flow. The valve sequence developed is presented in Figure 28. Using this sequence, a satisfactory transient and steady operation were achieved over the entire range of accumulator demands.

Thus far, discussion has been limited to component testing, resolution of problems associated with these tests, and development of an operating sequence for system testing. Several significant items were demonstrated during PCA system testing, and data from the last test will be used to illustrate these items.

The last test conducted on the PCA consisted of an initial run followed by four recycles which were initiated and terminated automatically at the minimum and maximum accumulator pressures of 276 and 552 N/cm^2. The initial test was started with all accumulator demand valves open. The valves were then closed sequentially and operation terminated at the maximum accumulator pressure. Subsequent recycles were initiated with zero, one, two, and three demand valves open respectively. The accumulator pressure for this test is presented in Figure 29.

The ability to achieve realistic response times was one of the primary areas of concern with PCA operation. Response time was defined as the time between initiation of PCA operation and the time that sufficient flow could be provided to stabilize accumulator pressure. Response time is shown graphically in Figure 2. Studies have shown system weight to be highly dependent on response time. Data presented in Reference 2 shows that if response time of the PCA considered for use in the Space Shuttle Booster APS increases from the design value of 0.5 second to 1.5 seconds, system weight will increase by 454 kg.

The response time for the last recycle is shown in the expanded accumulator pressure trace of Figure 30. This recycle represents the worst-case start condition of maximum accumulator demand flow. The response time of 0.77 seconds, which was the longest observed, demonstrates that satisfactory response times can be achieved. It should be noted that this was demonstrated using existing hardware that was not designed specifically for this application. With hardware designed for a PCA it should be possible to reduce the response time.

The ability to maintain system control while achieving realistic response times was also an area of concern. Start transient data from these PCA tests showed the system to be controllable over the entire range of accumulator demand flows. A difference in start characteristics was noted between the initial run and the recycles. This difference was most pronounced in pump discharge pressure (see Fig. 31). The initial run had a smooth buildup whereas the recycles showed a marked plateau in the 276 N/cm^2 pressure range. This difference can be explained by the difference in hardware temperatures between the initial run and the recycles. On the initial run the system downstream of the turbopump was at ambient temperature, and for the subsequent recycles the system was chilled. Minor differences also occurred between recycles as evidenced by the data in Figure 31. The data was examined in an attempt to explain these differences; however, no single influencing factor could be found. Although minor start transient differences were noted over the range of operating conditions tested, the system was controllable and repeatable.

CONCLUSIONS

This program has demonstrated the feasibility of building and operating a propellant conditioning assembly of the type required for a cryogenic auxiliary propulsion system. Realistic response times were demonstrated over the entire range of operating conditions, and system start characteristics were shown to be predictable and repeatable. It was also demonstrated that acceptable system control can be achieved by maintaining constant flow $(P/\sqrt{T})$ through the turbine and gas generator.

Two potential problem areas were identified. These were inlet line dynamics and formation of vapor during the cutoff transient. The rapid start requirements of the PCA result in the system being susceptible to large amplitude inlet pressure oscillations which could be detrimental to system operation. Systems with long inlet lines are especially susceptible to this problem. Although the surge of supercritical hydrogen back through the pump at cutoff was reduced to an acceptable level for these tests, a potential problem would exist in a flight system due to introduction of vapor into the zero-gravity acquisition system. It should be possible to overcome these potential problems through judicious system design.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812, November 1973
731-13-48-0000

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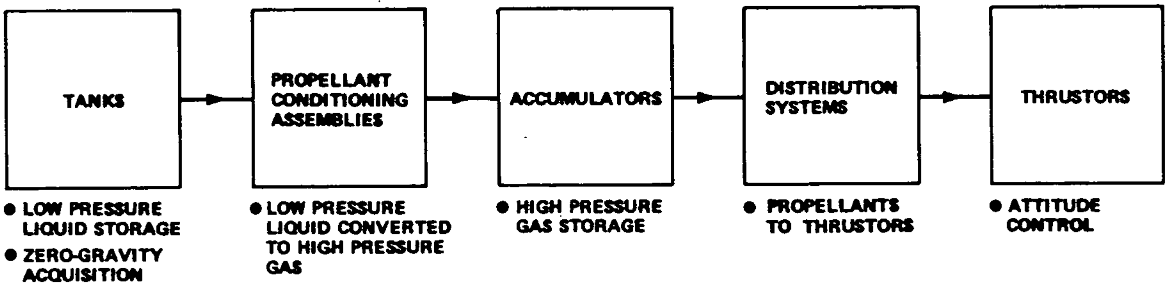


Figure 1. Elements of cryogenic auxiliary propulsion systems.

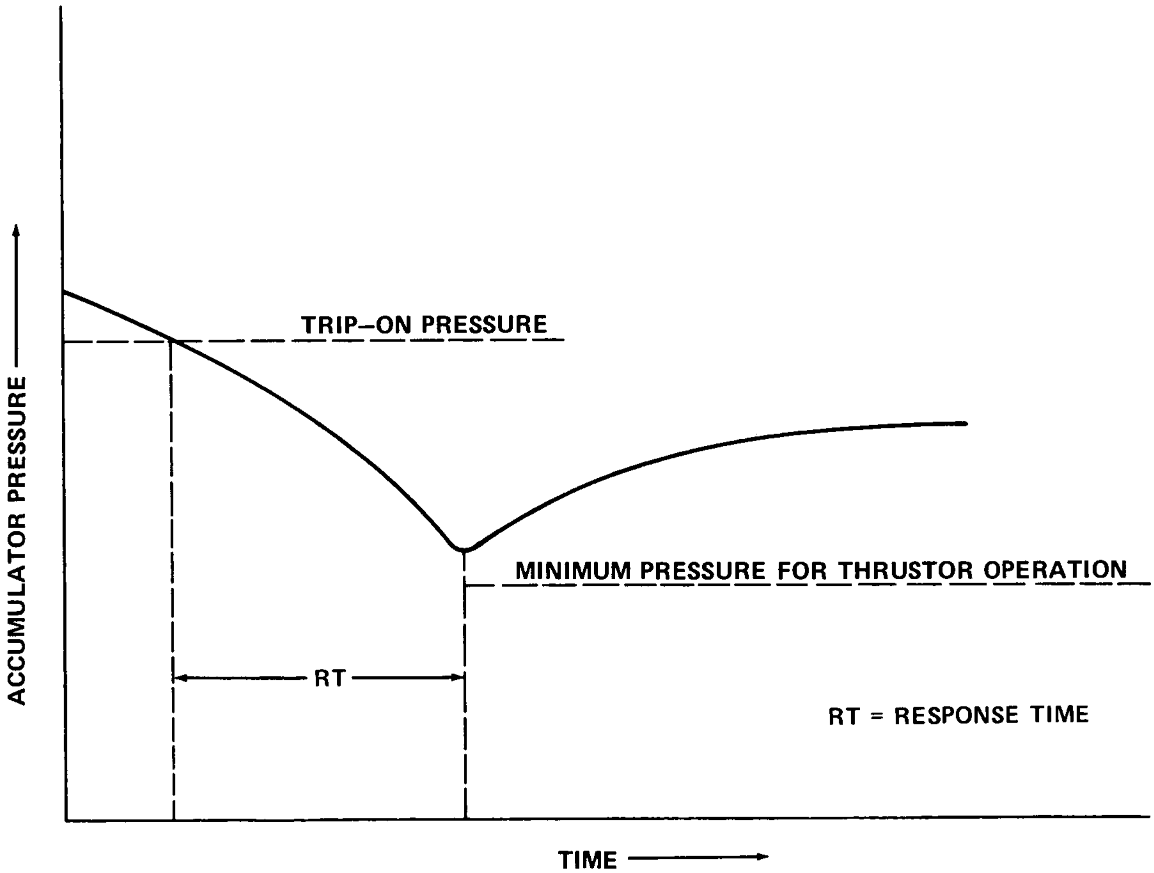


Figure 2. PCA response time.

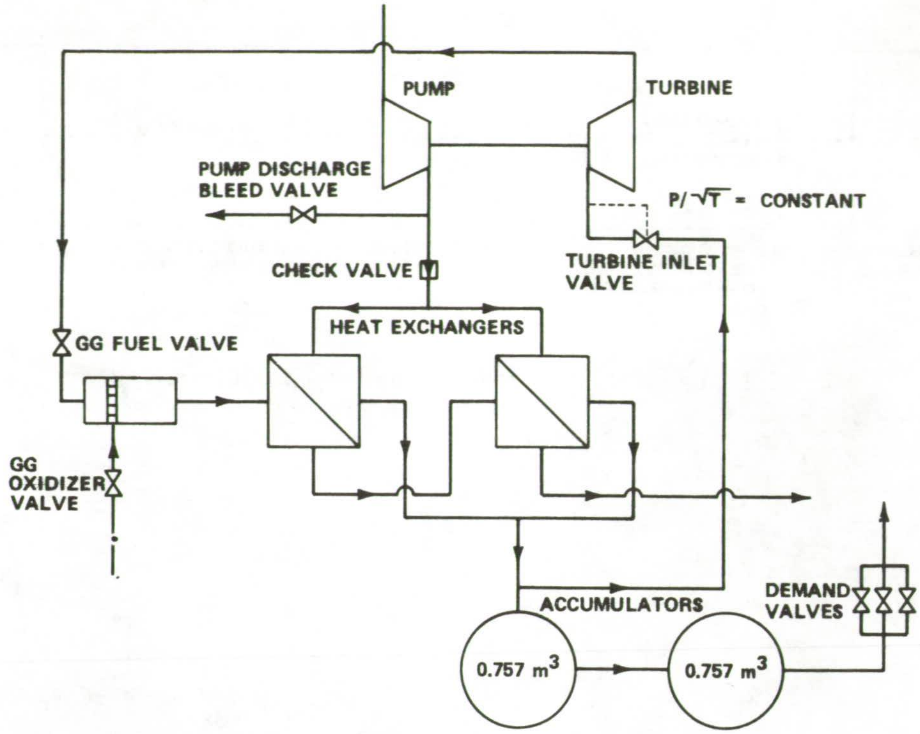


Figure 3. Propellant conditioning assembly configuration.

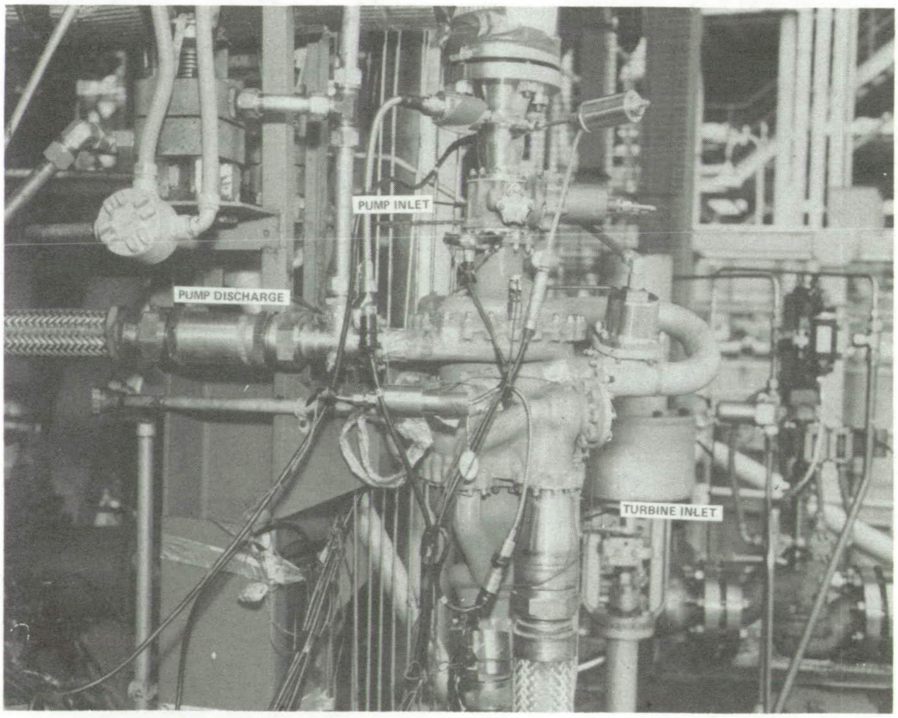


Figure 4. RL-10 turbopump.

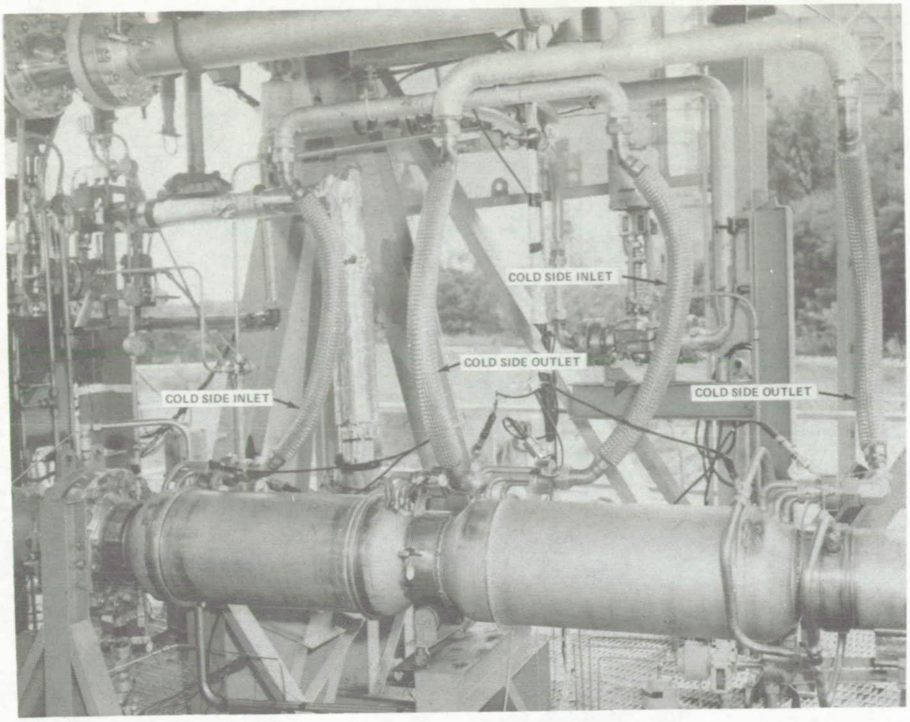


Figure 5. H-1 heat exchangers.

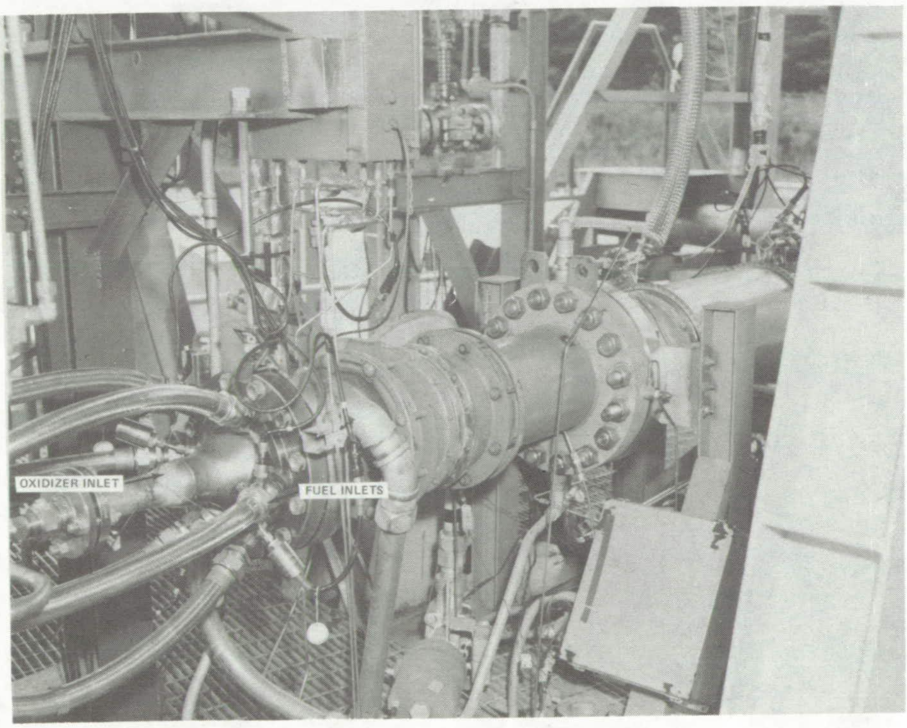


Figure 6. Gas generator.

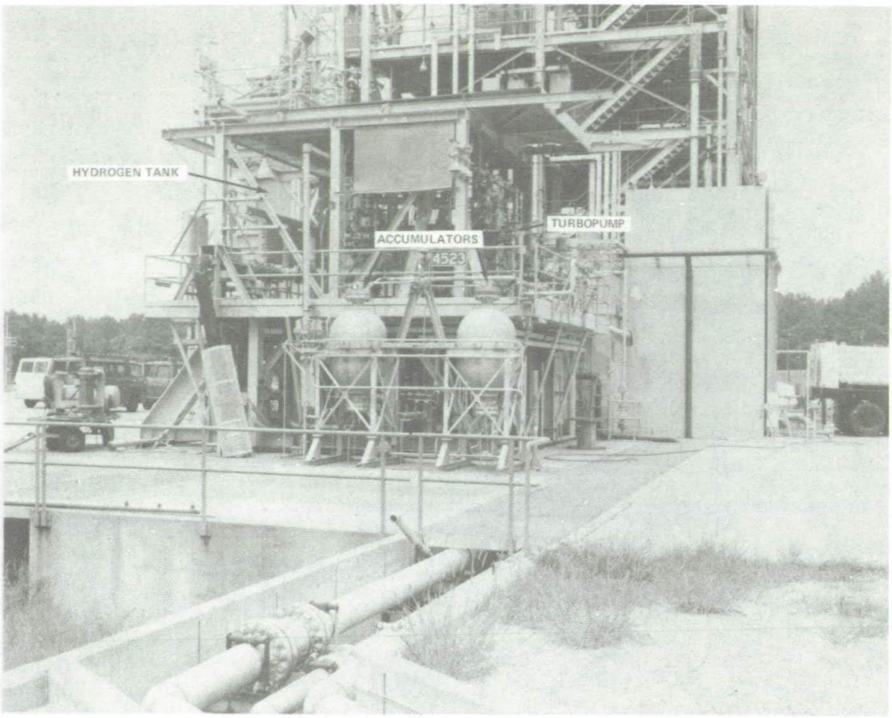


Figure 7. Accumulator.

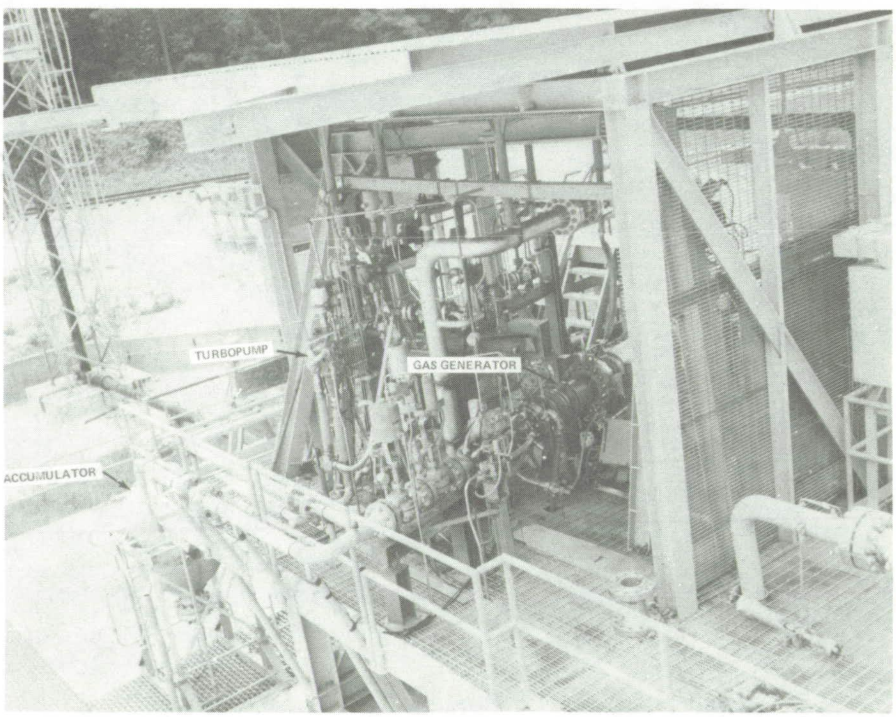


Figure 8. Propellant conditioning assembly.

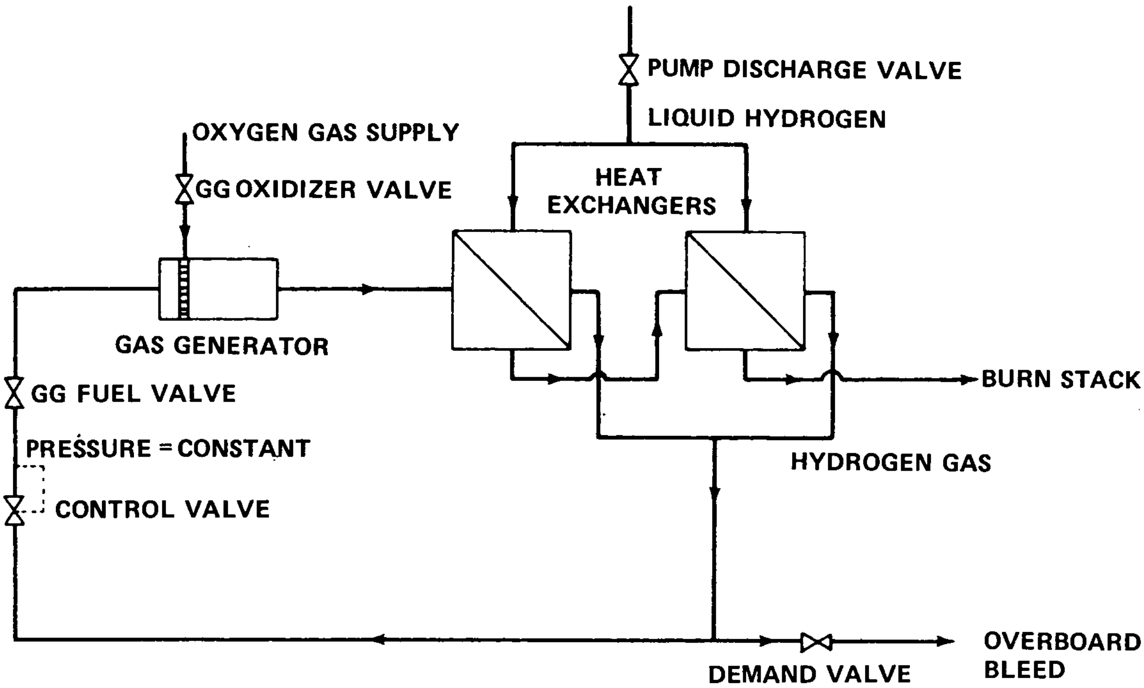


Figure 9. Gas generator – heat exchanger test configuration.

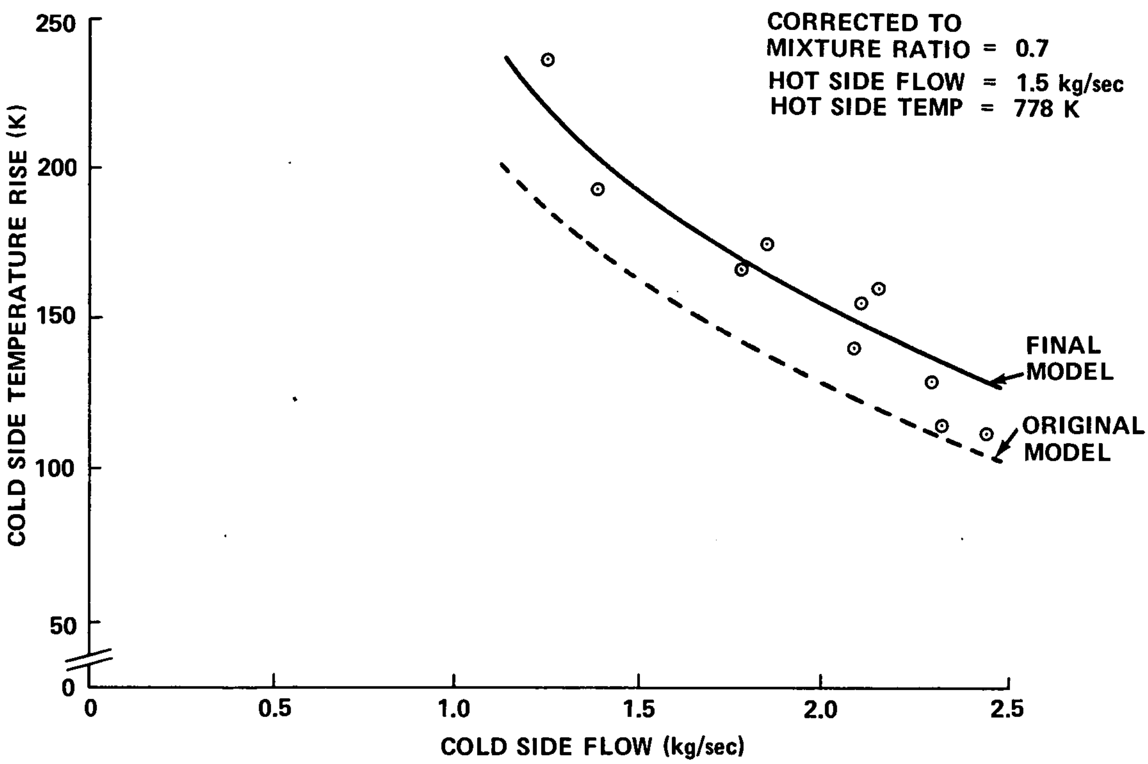


Figure 10. Heat exchanger performance.

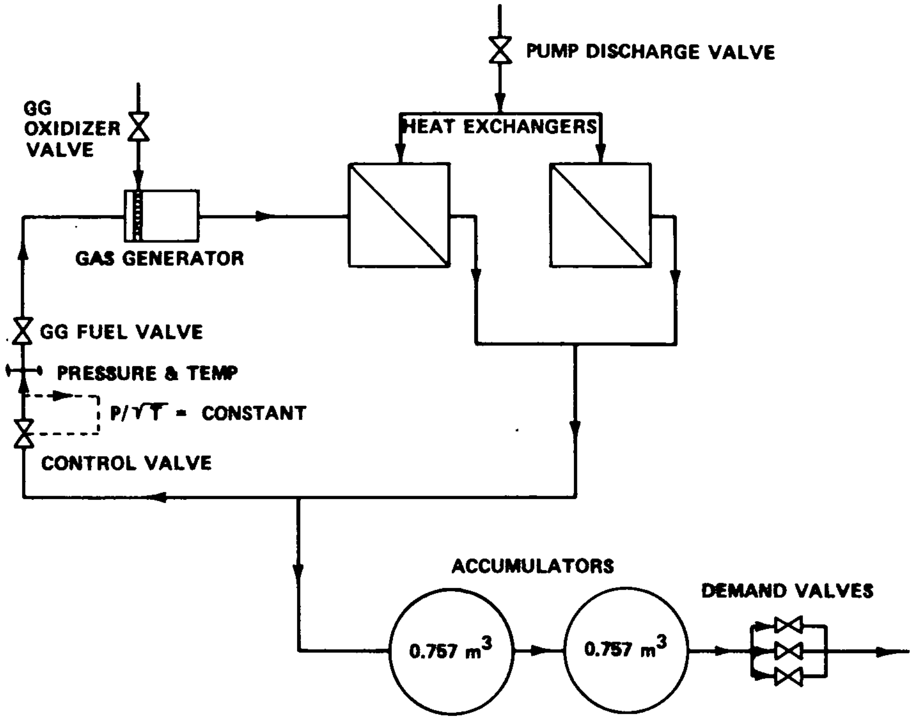


Figure 11. Gas generator – heat exchanger test configuration with flow control.

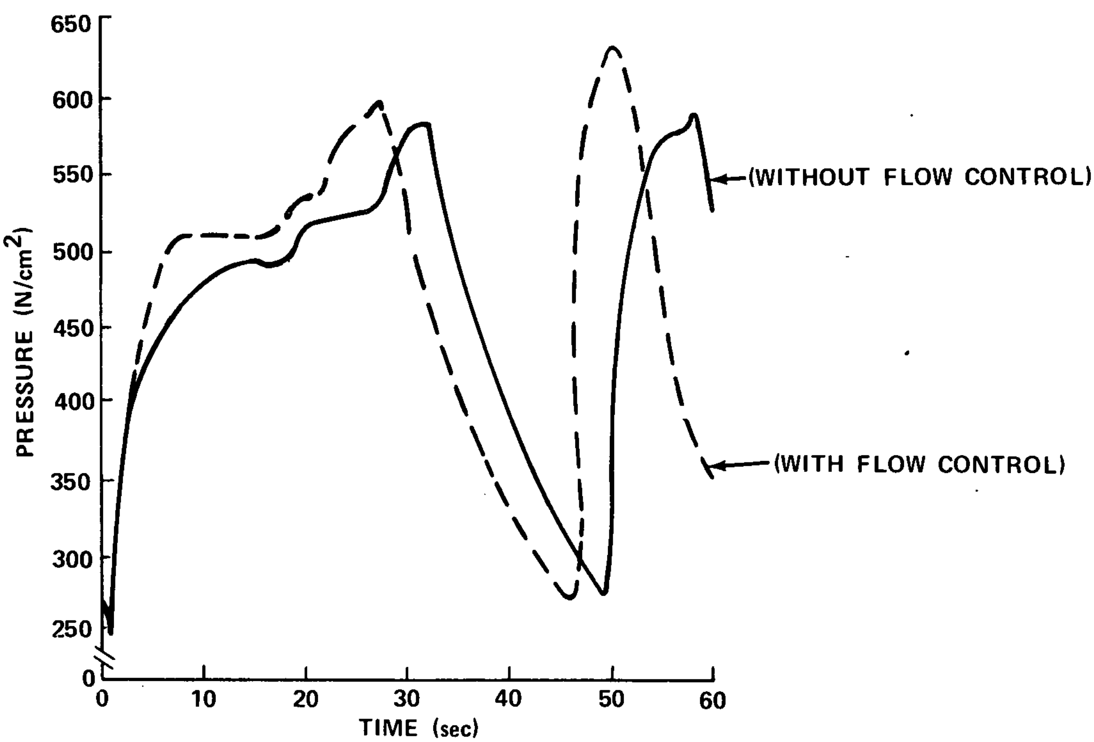


Figure 12. Accumulator pressure.

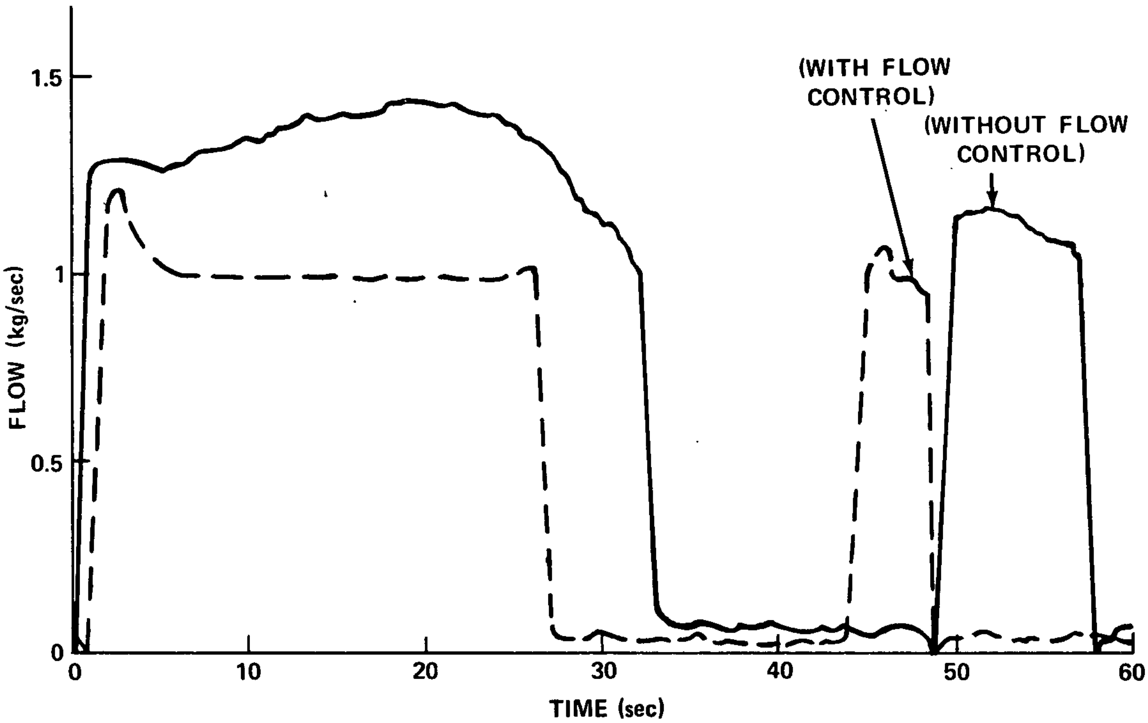


Figure 13. Gas generator fuel flow.

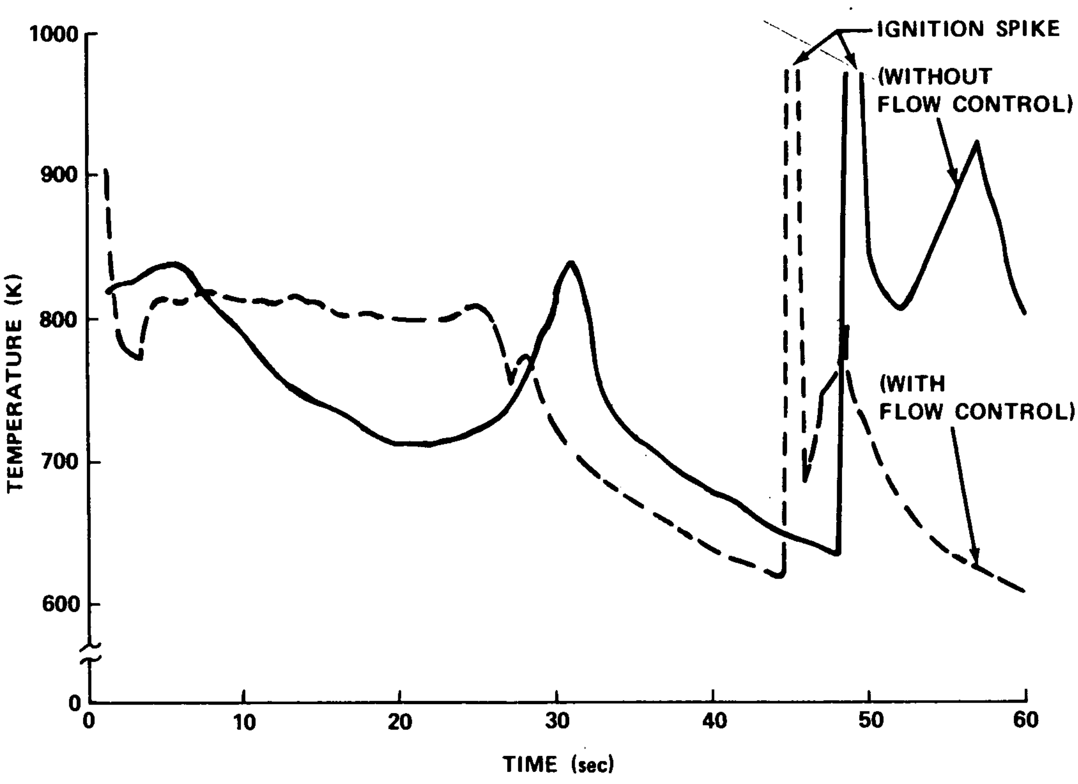
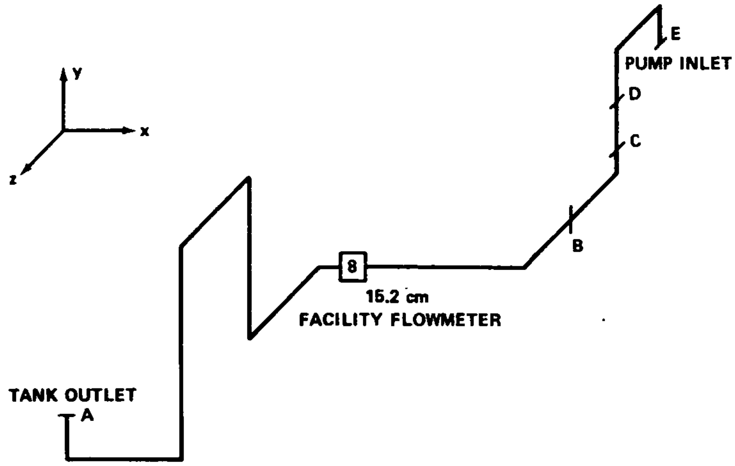


Figure 14. Gas generator combustion temperature.



SECTION	LENGTH (m)	DIAMETER (cm)	TYPE	INSULATION
AB	25.3	15.2	SCHEDULE 80	VACUUM JACKET
BC	3.66	10.2	SCHEDULE 80	VACUUM JACKET
CD	1.22	7.6	SCHEDULE 80	VACUUM JACKET
DE	6.10	6.35	SCHEDULE 80	FOAM

LINE INERTIA = 436 sec^2/m^2

Figure 15. Suction line configuration.

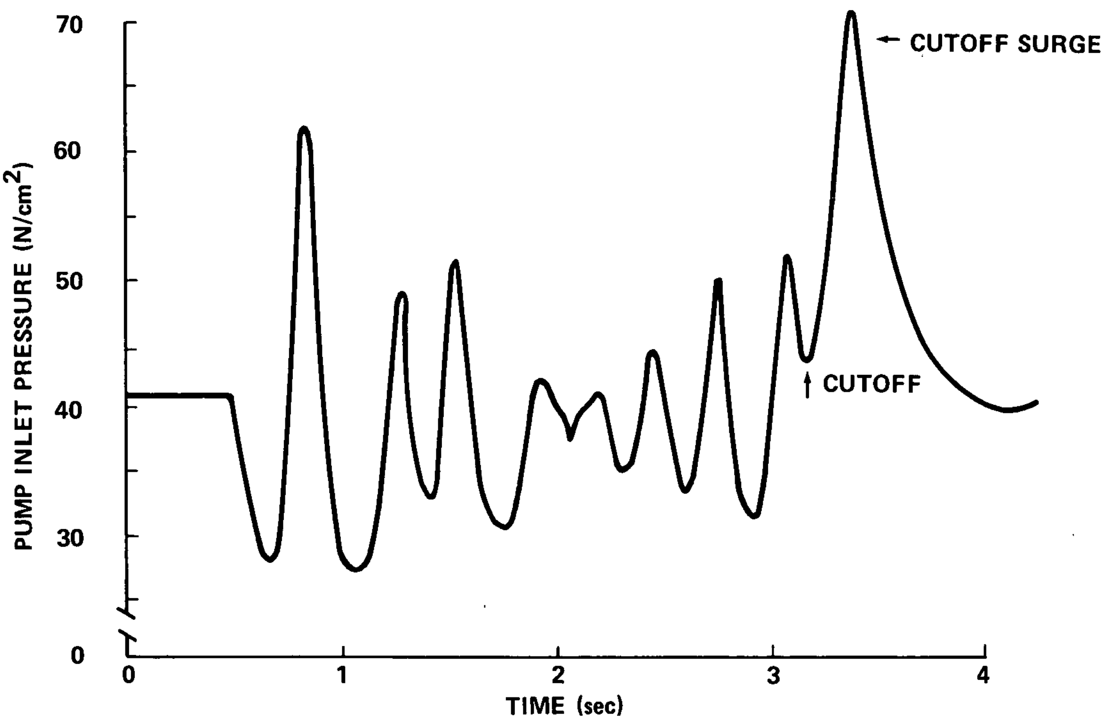


Figure 16. Pump inlet pressure.

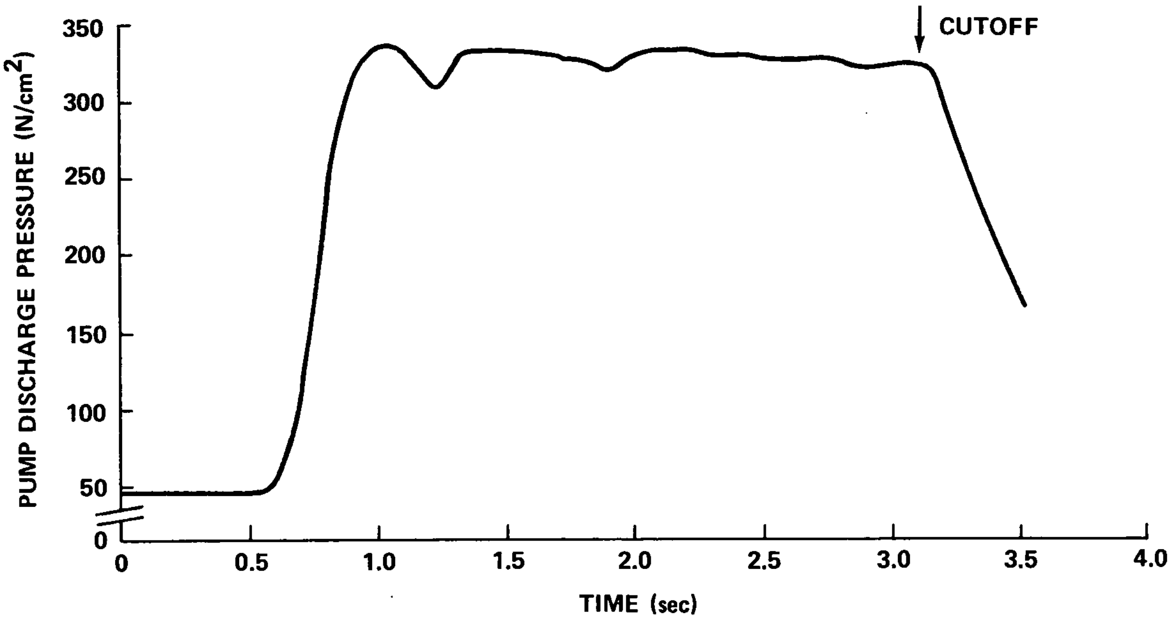


Figure 17. Pump discharge pressure.

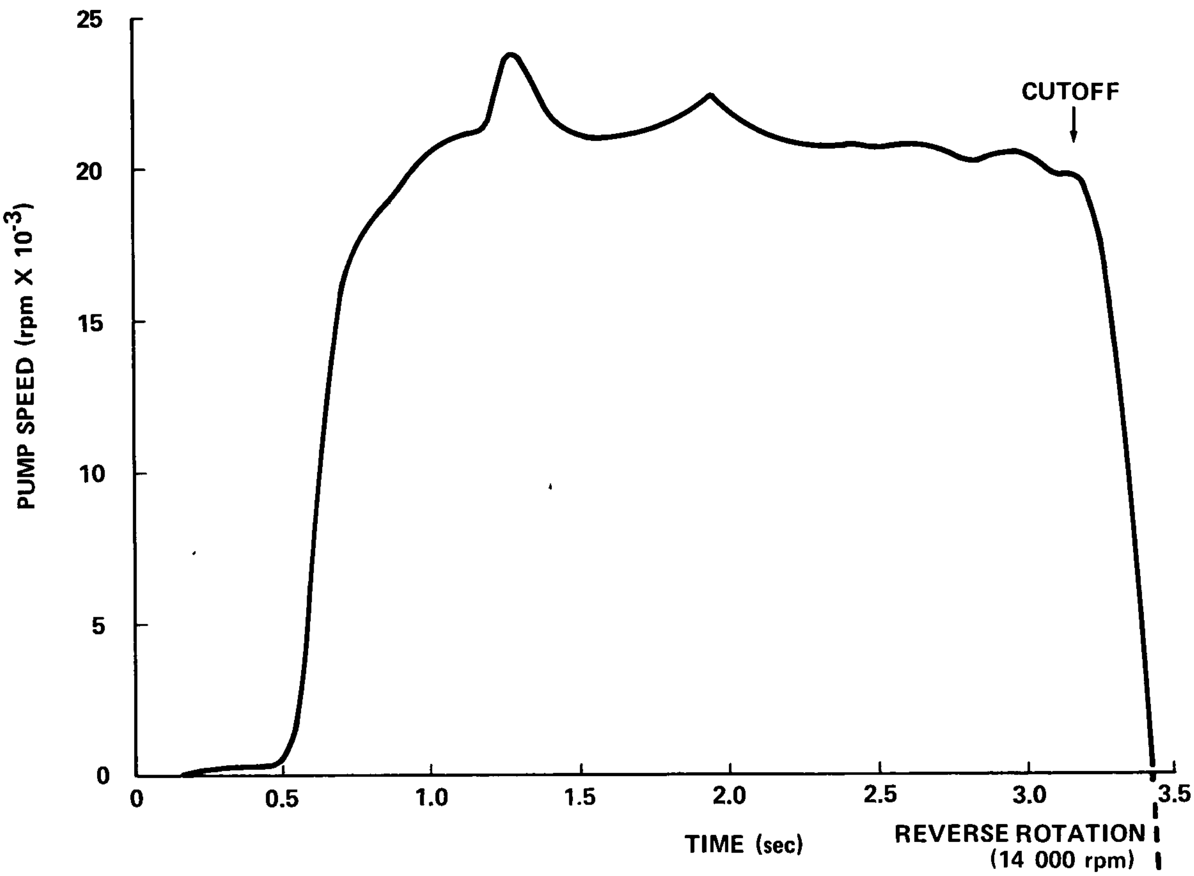


Figure 18. Pump speed.

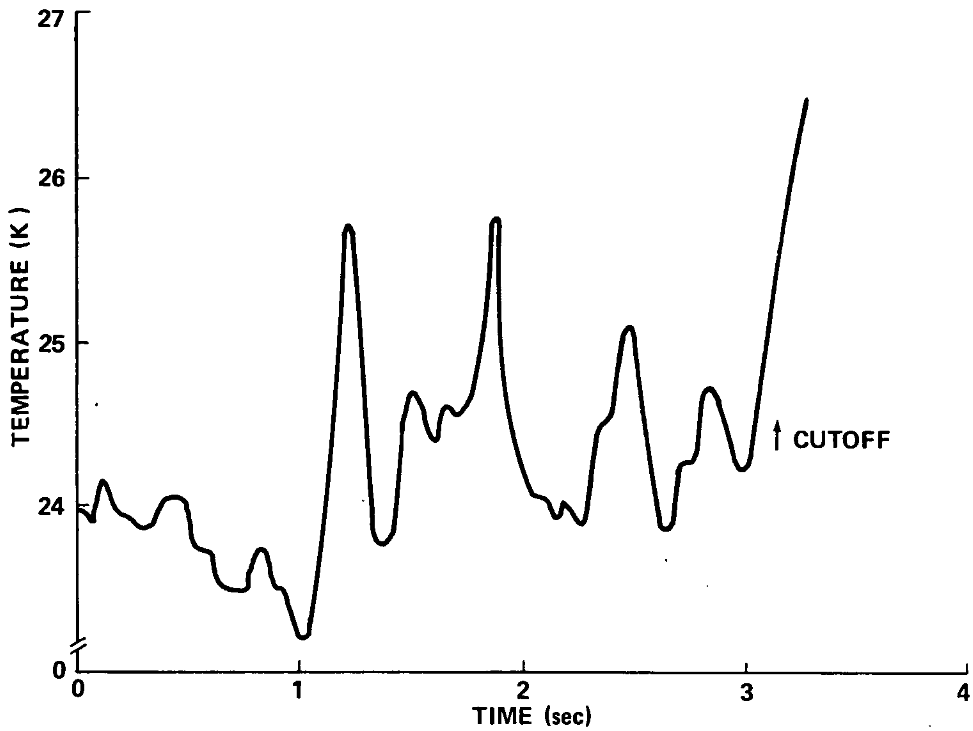


Figure 19. Pump inlet temperature.

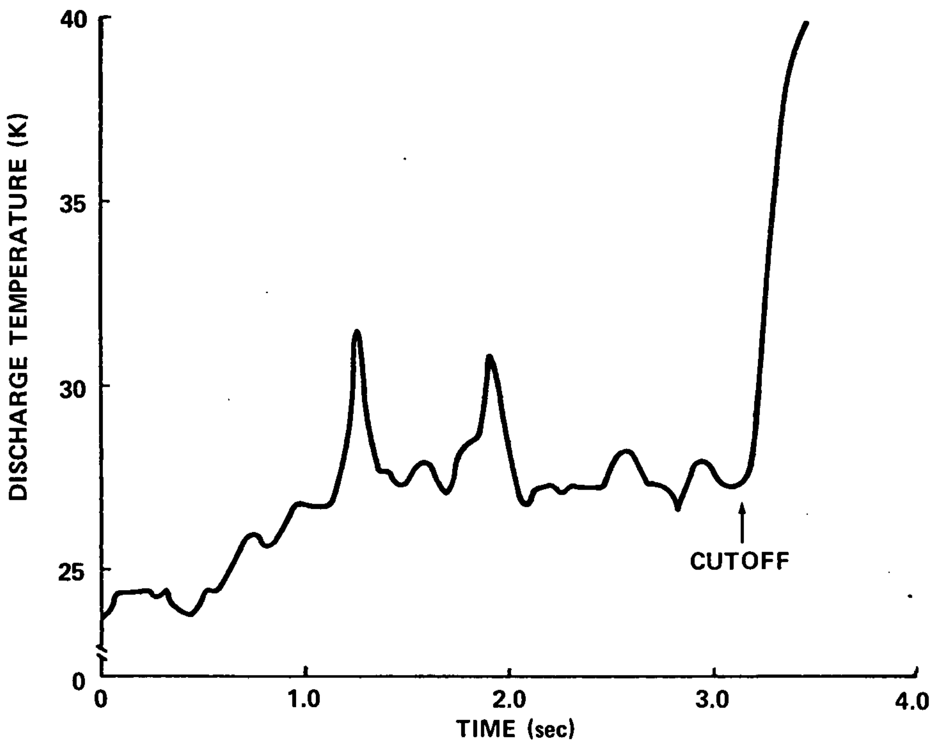


Figure 20. Pump discharge temperature.

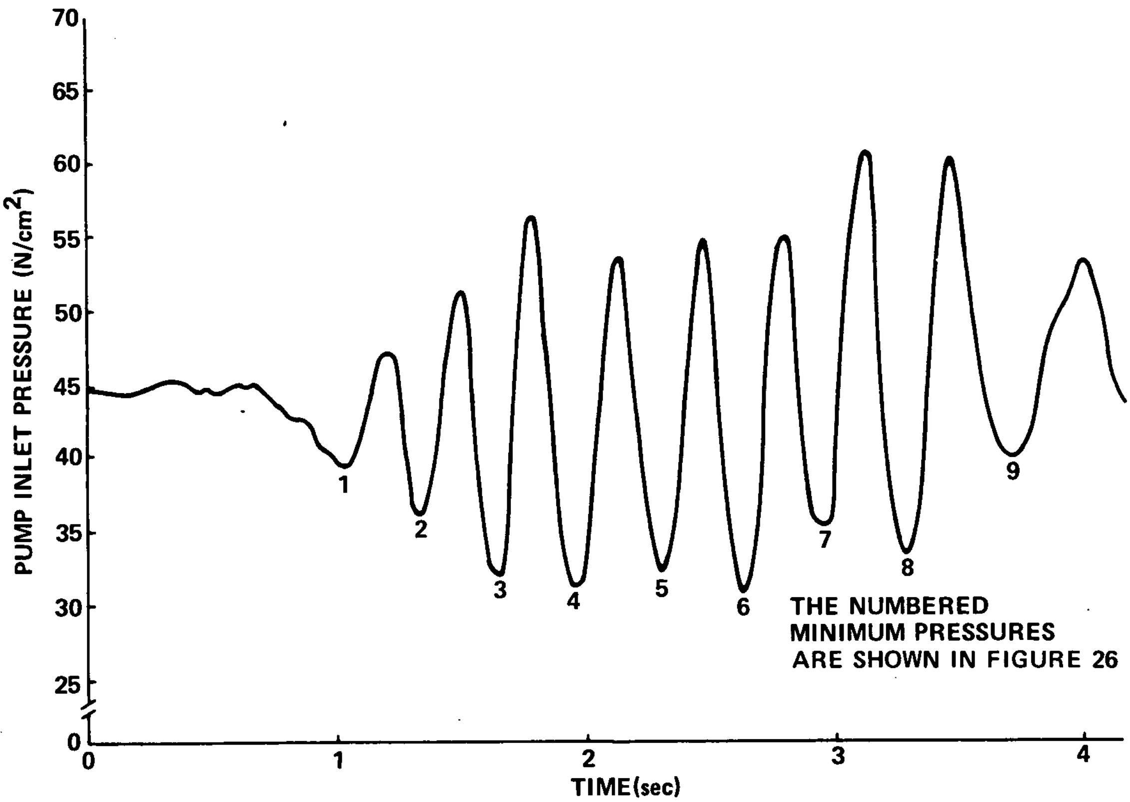


Figure 21. Pump inlet pressure – increased start time and NPSH.

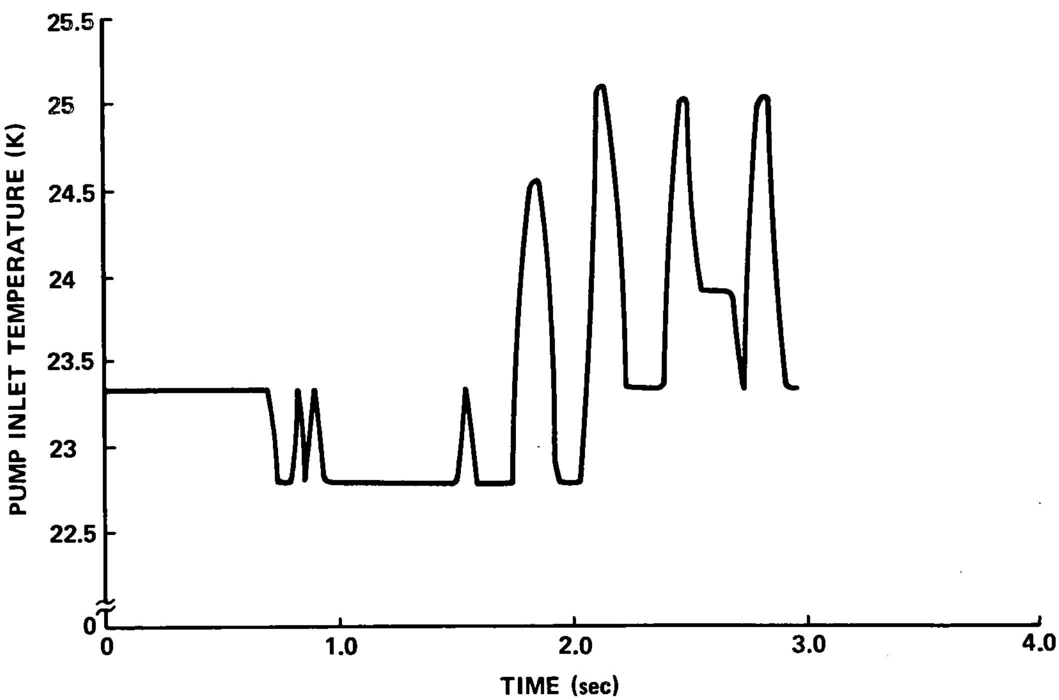


Figure 22. Pump inlet temperature – increased start time and NPSH.

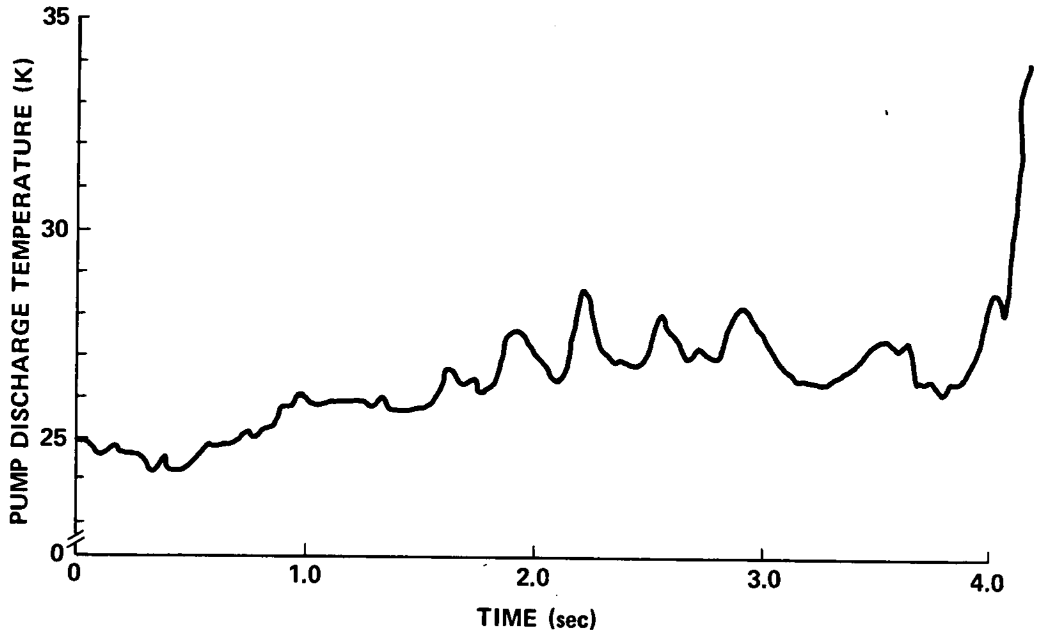


Figure 23. Pump discharge temperature – increased start time and NPSH.

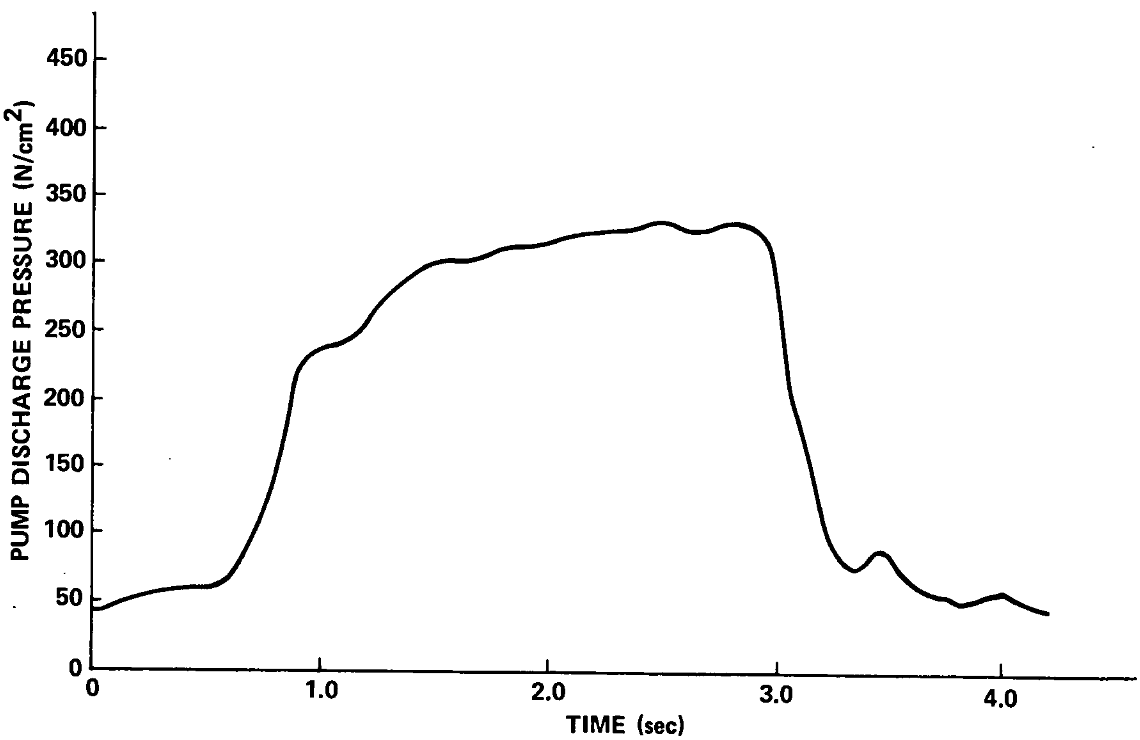


Figure 24. Pump discharge pressure – increased start time and NPSH.

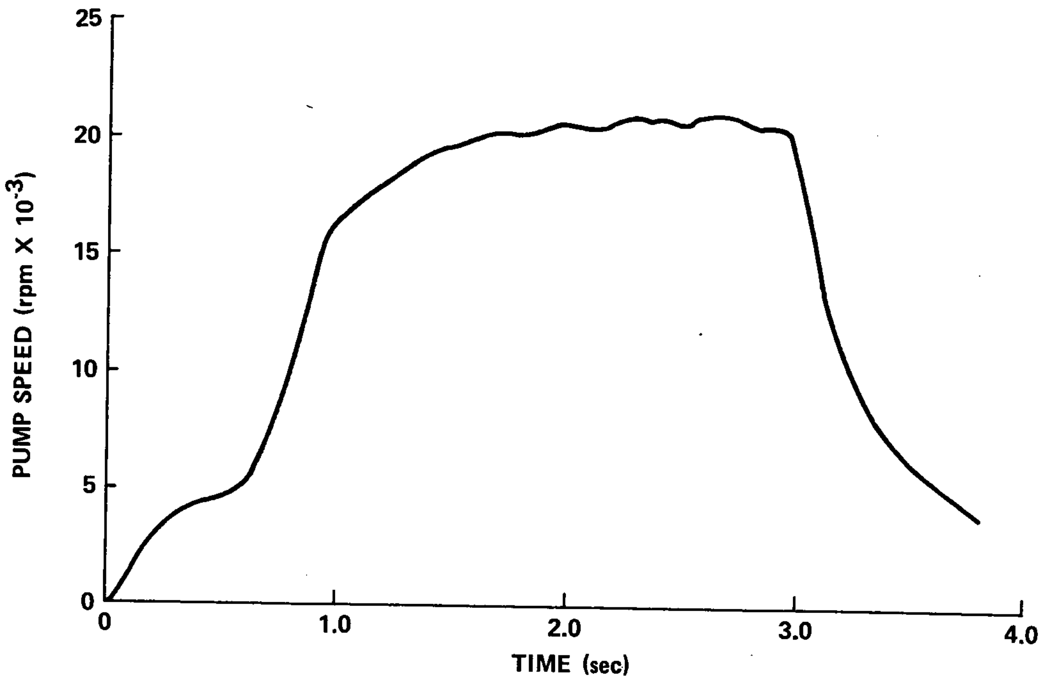


Figure 25. Pump speed – increased start time and NPSH.

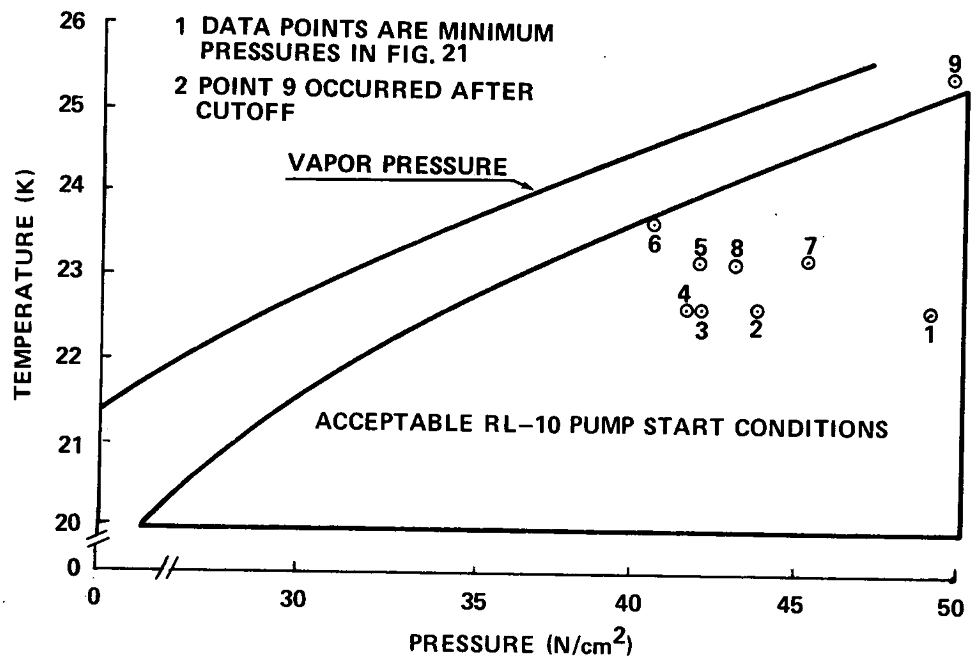


Figure 26. Inlet conditions at minimum pressures.

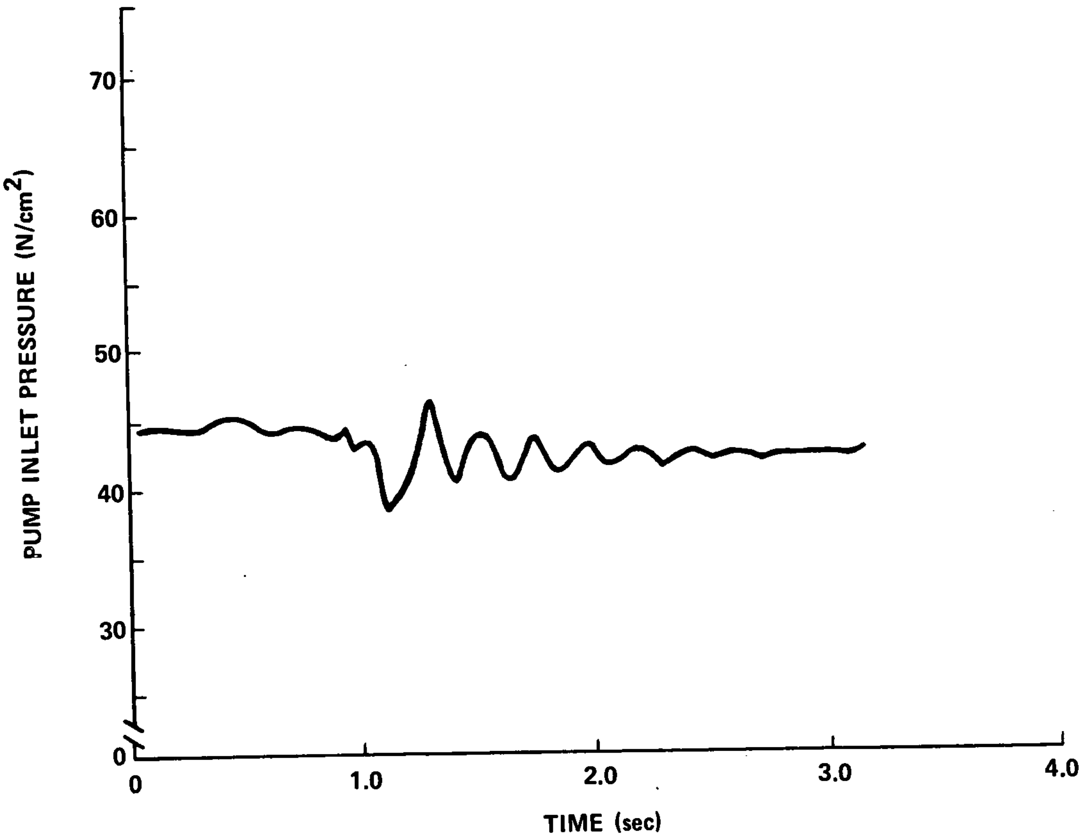


Figure 27. Pump inlet pressure – early pump discharge bleed valve closure.

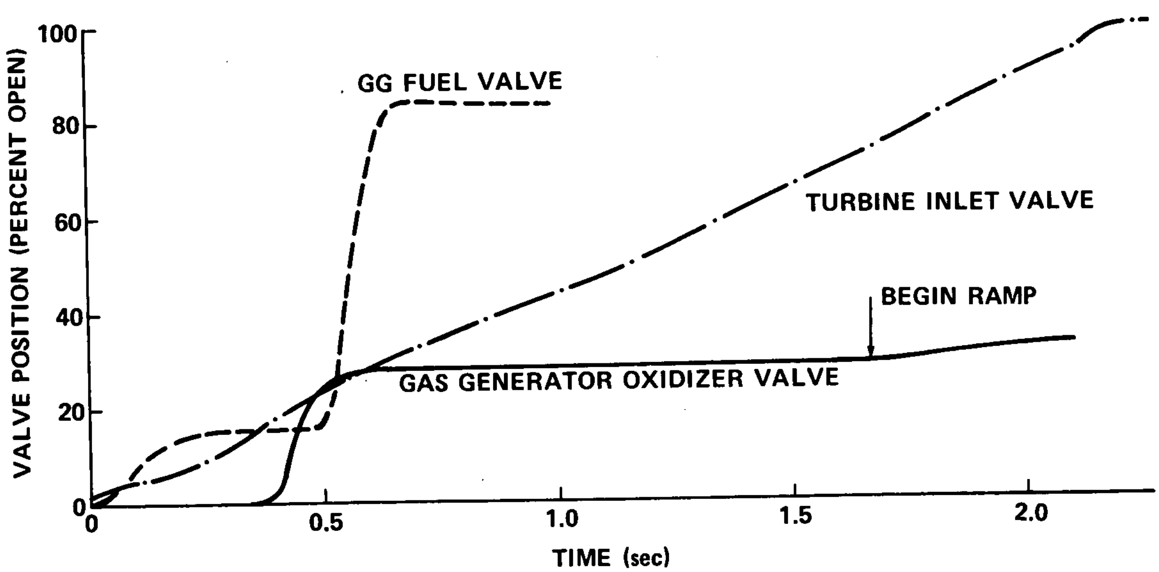


Figure 28. PCA start sequence.

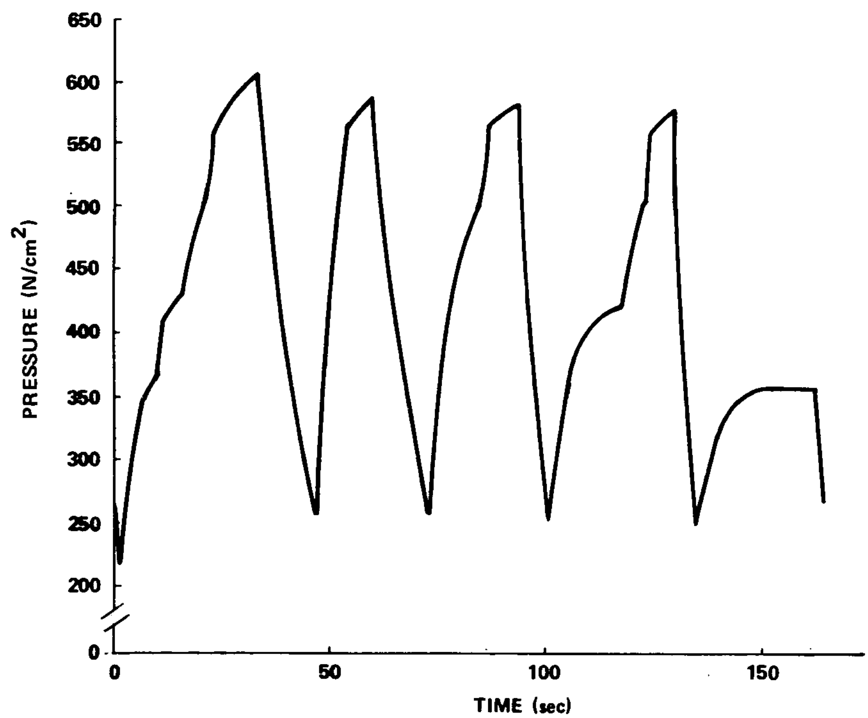


Figure 29. Accumulator pressure PCA recycle test.

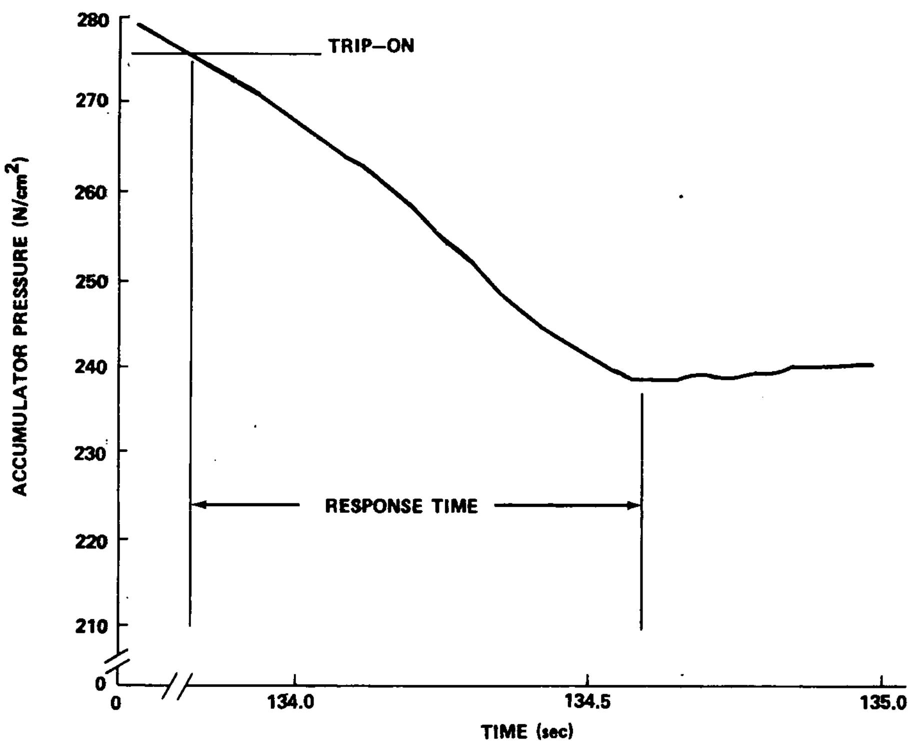


Figure 30. Maximum PCA response time.

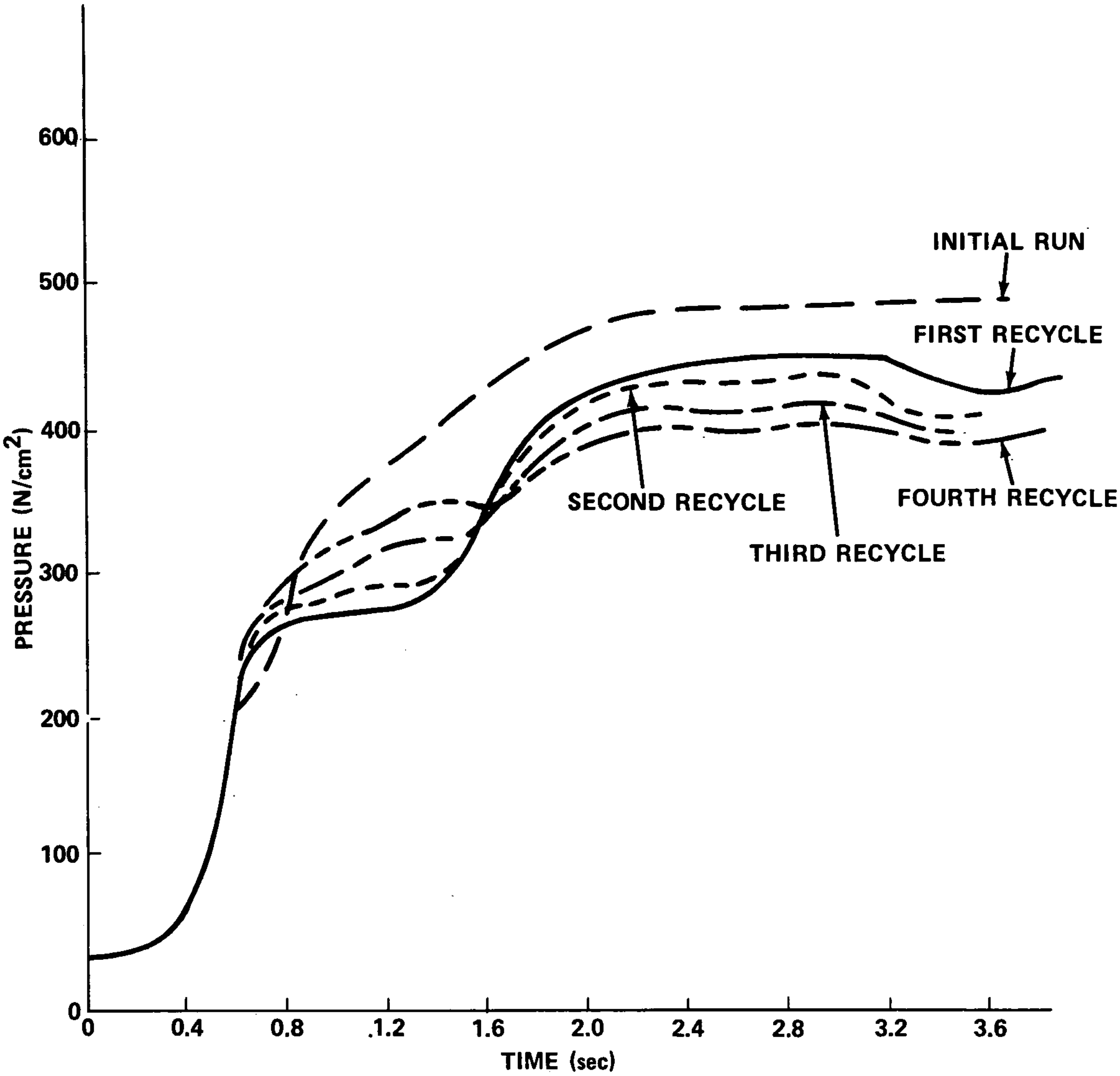


Figure 31. Pump discharge pressure – PCA recycle test.

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